PLASMA-FILLED DIODE FOR HIGH DOSE-RATE BREMSSTRAHLUNG *

B. V. Weber,[ξ] D. D. Hinshelwood, D. P. Murphy, and S. J. Stephanakis
Plasma Physics Division, Naval Research Laboratory
Washington, DC 20375 USA

Abstract

A plasma-filled diode (PFD) can produce high dose-rate ($>2\times10^{12}$ rad/s) bremsstrahlung over small areas (100 cm^2) on the Saturn generator at Sandia. A PFD was developed for this purpose using the Gamble II generator at NRL. The maximum dose-rate was obtained with a conduction time of 40 ns, after which the voltage increased to 1.8 MV and the total current in the diode was 0.5 MA. The 3.6-Ohm maximum impedance is the same as for a hypothetical vacuum diode with an AK gap of 0.6 mm. The x-ray pulse width (FWHM) was 8 ns, much less than the typical 50 ns FWHM with a vacuum diode. This PFD was adapted to the higher-current (6-8 MA) Saturn generator by making a 10-cm diameter circular array of 6-12 isolated PFDs. Higher dose rates were obtained using fewer PFDs; about 1×10^{12} rad/s with the 12-PFD array, 2×10^{12} with 9 PFDs and 4×10^{12} with 6 PFDs. Analyses based on electrical and radiation diagnostics indicate that 40-75% of the electrical current produces radiation at the time of maximum dose rate. The x-ray pulse width was typically 12-15 ns, about half of the pulse width for standard (vacuum) bremsstrahlung diodes on Saturn. This system, with improvements in reproducibility at high dose rate, could provide a high dose-rate, small-area testing capability for Saturn.

I. PFD DEVELOPMENT ON GAMBLE II

Plasma-filled diodes (PFDs) have characteristics that make them attractive as sources of high dose-rate, small area bremsstrahlung. The PFD configuration described in this paper is shown in Fig. 1. Plasma is injected across the 1-cm anode-cathode (AK) gap using a plasma gun inside the 1-cm diameter center conductor. The plasma initially short-circuits the diode. After the short-circuit phase, the PFD impedance increases and an electron beam forms that generates bremsstrahlung in the high-Z (tantalum) anode.

PFDs have several advantages over standard vacuum diodes for this particular application. The initial short circuit phase allows current to build up at low voltage, providing a bias magnetic field to reduce losses in vacuum transmission lines and vacuum convolutes. The eventual PFD impedance can be much smaller than is possible with a vacuum diode, with a sub-mm equivalent gap (in the plasma). Finally, the fast-rising PFD impedance acts like an opening switch and can result in voltage gain and pulse shortening, both desirable for high dose-rate applications.

The PFD in Fig. 1 was fielded on the Gamble II generator (1 MA, 2 MV, 100 ns) to test its suitability for higher current applications where many similar PFDs would be fielded in parallel. Several parameters were varied to determine the conditions for maximum dose rate, including: the time delay between the start of the plasma gun current and the start of the Gamble II current; the distance between the gun and the end of the cathode tube; and the initial AK gap. The AK gap was located at the end of a 5-cm long coaxial section, a sufficient distance to allow inductive isolation among multiple PFDs. The anode diameter in this section was chosen to be 3 cm; experiments with 2-cm diameter anodes resulted in excessive current loss.

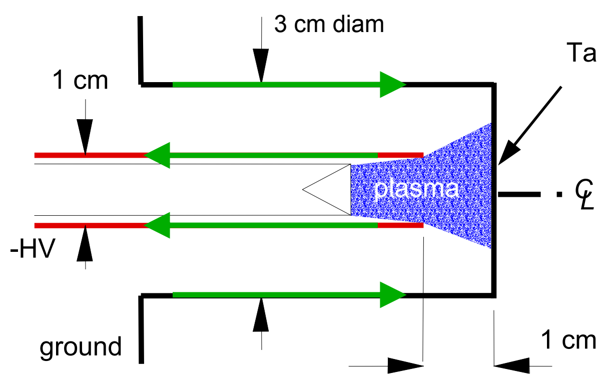

Figure 1. PFD configuration tested on Gamble II.

Data from the Gamble II PFD shot that produced the highest dose rate are shown in Fig. 2. For this shot, plasma was injected starting 1.3 µs prior to the start of the Gamble II current. The current increases for 40 ns to about 0.5 MA at the time of the start of the x-ray signal. The PFD voltage is small during this time, indicating that the plasma is shorting the AK gap. After this low-impedance phase, the voltage increases to 1.8 MV, the current decreases slightly (as the increased impedance loads down the generator) and a short-duration (8-ns

* Work supported by ONR and Sandia National Laboratories
ξ email: weber@suzie.nrl.navy.mil

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2003	**N/A**	**-**

4. TITLE AND SUBTITLE	
Plasma-Filled Diode For High Dose-Rate Bremsstrahlung	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Plasma Physics Division, Naval Research Laboratory Washington, DC 20375 USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License., The original document contains color images.

14. ABSTRACT

A plasma-filled diode (PFD) can produce high dose-rate (>2×1012 rad/s) bremsstrahlung over small areas (100 cm2) on the Saturn generator at Sandia. A PFD was developed for this purpose using the Gamble II generator at NRL. The maximum dose-rate was obtained with a conduction time of 40 ns, after which the voltage increased to 1.8 MV and the total current in the diode was 0.5 MA. The 3.6-Ohm maximum impedance is the same as for a hypothetical vacuum diode with an AK gap of 0.6 mm. The x-ray pulse width (FWHM) was 8 ns, much less than the typical 50 ns FWHM with a vacuum diode. This PFD was adapted to the higher-current (6-8 MA) Saturn generator by making a 10-cm diameter circular array of 6-12 isolated PFDs. Higher dose rates were obtained using fewer PFDs; about 1×1012 rad/s with the 12-PFD array, 2×1012 with 9 PFDs and 4×1012 with 6 PFDs. Analyses based on electrical and radiation diagnostics indicate that 40-75% of the electrical current produces radiation at the time of maximum dose rate. The x-ray pulse width was typically 12-15 ns, about half of the pulse width for standard (vacuum) bremsstrahlung diodes on Saturn. This system, with improvements in reproducibility at high dose rate, could provide a high dose-rate, small-area testing capability for Saturn.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

FWHM) x-ray pulse is measured. At the time of maximum x-ray emission, the PFD impedance is 3.6 Ω. A vacuum diode with this impedance and 5-mm radius would have an AK gap of about 0.6 mm. The voltage and x-rays decrease rapidly after their maxima, probably due to electrode plasmas crossing the small plasma gap.

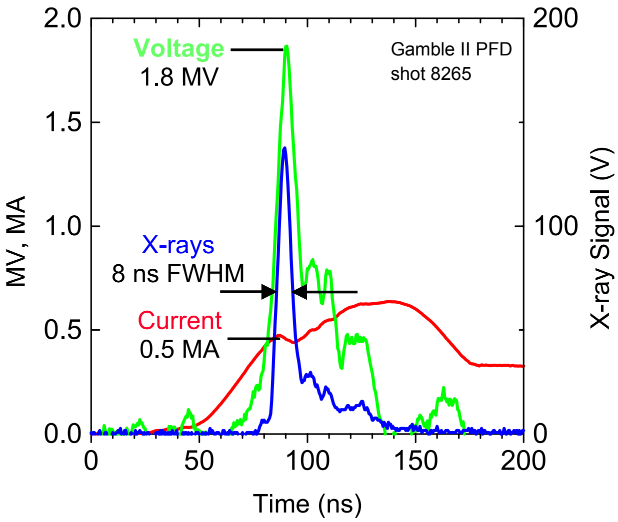

Figure 2. Data from the highest dose-rate PFD shot on Gamble II.

Experiments with reduced plasma delay (lower initial plasma density) opened at lower current and resulted in lower dose rate. Shots with increased plasma delay (higher initial density) opened when the current exceeded 0.6 MA and also resulted in lower dose rate. The reasons for the maximum dose rate at about 0.5 MA conducted current is not well understood, but the operating point is sufficient for scaling to Saturn at higher current.

II. SATURN PFD EXPERIMENTS

The standard bremsstrahlung configuration used on the Saturn generator consists of three concentric ring diodes.[1] In this mode, the total current is about 12 MA, the voltage is 1.8 MV and the dose rate is 2×10^{12} rad/s over 750 cm^2 (about 30-cm diameter). The x-ray pulse FWHM is about 20 ns, although smaller pulse width is desired for testing purposes.

To complement the large area testing mode, a small-area mode is desired for Saturn. In this mode, a thick tungsten shield with a 12.5 cm aperture is used to expose small area (150 cm^2) objects and shield ancillary equipment from x-rays. When used with the standard 3-ring configuration, the tungsten shield reduces the dose rate by about half. Reducing the diameters of the ring diodes is one technique being investigated for improving the small-area mode, but so far, losses in the power feeds has limited the dose rate to less than that available from the standard configuration.

The new technique described here for the small-area Saturn bremsstrahlung source uses a circular array of PFDs, identical to those tested on Gamble II. The PFDs are connected to the double post-hole convolute[2] used for Z-pinch experiments on Saturn. This way, the convolute concentrates the generator current to a small diameter (10 cm), approximately the desired diameter for the small-area bremsstrahlung source. A cross section of this hardware with the PFDs is shown in Fig. 3.

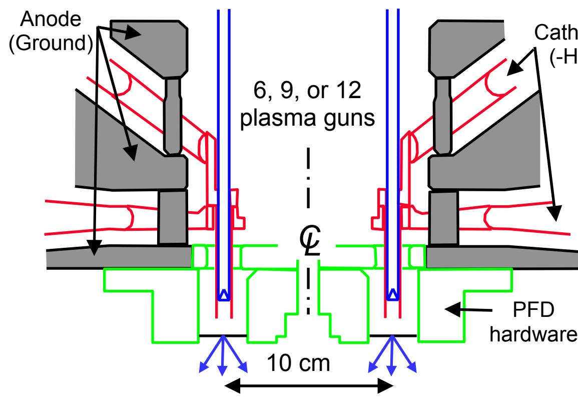

Figure 3. PFD array connected to Saturn post-hole convolute.

In the Z-pinch configuration, the short-circuit current is about 10 MA, 20% less than the total diode current for the standard bremsstrahlung configuration. The current rise time is 50 ns, similar to optimum PFD conditions on Gamble II. A circular array of 12 isolated PFDs on Saturn, with the same plasma conditions as on Gamble II, should result in a 6-MA, 1.8 MV pulse with an x-ray FWHM greater than 8 ns, depending on the jitter between the individual PFDs.

The PFDs are isolated so they operate independently. Each 1-cm PFD tube extends from the cathode plate through 2-cm diameter holes in the anode. The section below the holes (“PFD hardware” in Fig. 3) was made in two different versions. The version used with 9 PFDs consists of 3-cm diameter holes bored through a solid piece. Experiments on Gamble II demonstrated that the radial gap between the PFD and the anode wall could not be less than 1 cm without significant current loss. The axial extent of the PFD anode is 5 cm, from the top of the plate with the holes to the tantalum x-ray converter. This distance is necessary, according to 3D computer simulations, to isolate the PFDs so the individual beams pinch on their respective axes, forming a circular pattern of intense x-ray sources, approximating a circular source. With 12 PFDs, the 3-cm cylindrical holes would overlap so instead the PFD hardware was made from two concentric cylinders, analogous to the return current conductors for a ring diode.

Data from 6-, 9-, and 12-PFD shots on Saturn are compared in Fig. 4. These selected shots produced the highest dose rate for each PFD configuration. (In the case of the 6-PFD configuration, this was the only shot.) For each shot, the current measured in the upstream MITLs and the far-field x-ray signal (measured with a scintillator-photodiode detector) are plotted. In addition, several parameters derived from other measurements are listed. Dose rate (1.5-4.3$\times 10^{12}$ rad/s) is defined as the dose measured with an array of TLDs located in a plane close to the x-ray converter package, averaged over a 10-cm diameter circular area, divided by the x-ray FWHM pulse width (13-16 ns). An effective endpoint voltage (1.1-1.7 MV) is determined from a stack of TLDs in the far field with various filters between them. Since this parameter is determined from time-integrated measurements, it is representative of the average voltage near the peak of the x-ray signal; the maximum voltage is probably a little larger. The electron current (2.8-5.0 MA) is derived from the peak dose rate and effective endpoint voltage, using an ITS analysis. The electrons are assumed to have normal incidence on the tantalum converter with reflected electrons re-injected into the tantalum to simulate the effect of the diode electric field (albedo suppression). These assumptions are consistent with the measured near-field dose pattern.

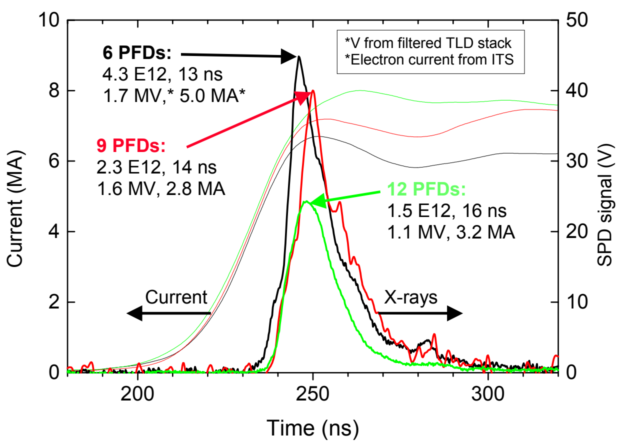

Figure 4. Current and x-ray (SPD) waveforms for the highest dose-rate shots with 6, 9, and 12 PFDs on Saturn.

The data in Fig. 4 show that as the number of PFDs decreases from 12 to 6, the peak dose rate increases, the FWHM decreases slightly, the MITL current at the time of peak x-ray signal decreases slightly and the voltage increases. Reducing the number of PFDs in parallel evidently increases the impedance, although the time delay was increased (increasing the initial plasma density) from 1.3 µs with 12 PFDs to 1.5 µs with 9 PFDs and 1.7 µs with 6 PFDs. The x-ray FWHM with 6 PFDs is 13 ns, about half of the value with the standard configuration, a feature that is desirable for some testing applications.

The time delay for the 12-gun shot in Fig. 4 was identical to the Gamble II (single PFD) shot in Fig. 2. The current at the time of maximum x-ray signal is 7 MA, a little more than 12 times the Gamble II current, 0.5 MA. These x-ray signals from Saturn and Gamble II peak at the same time relative to the current waveforms. The Gamble II x-ray pulse width is shorter (8 ns vs. 16 ns on Saturn), probably an indication that on Saturn, the 12 PFDs do not operate simultaneously. Improved simultaneity could further increase the dose rate and decrease the pulse width.

The electron currents listed in Fig. 4 indicate that only 40-75% of the full MITL current produces radiation. The remaining current could be lost in the MITL, the convolutes or in the form of ion current in the PFD. Reducing the current loss and thereby increasing the dose rate is a goal for future experiments.

The dose rates from the PFD experiments on Saturn are compared in Fig. 6 with nominal levels using the standard configuration. Shots with 12 PFDs match the previous small area capability, shots with 9 PFDs match the standard large area dose rate (but over a much smaller area), and the one shot with 6 PFDs exceeds the standard dose rate by about a factor of two. This 6-PFD shot was unusual in that the near-field dose distribution was highly asymmetric, and the near-field dose is not consistent with the far-field radiation measurements. The highest dose rate in Fig. 5 is therefore questionable, but is still greater than the best 9-PFD dose rate by at least 30%.

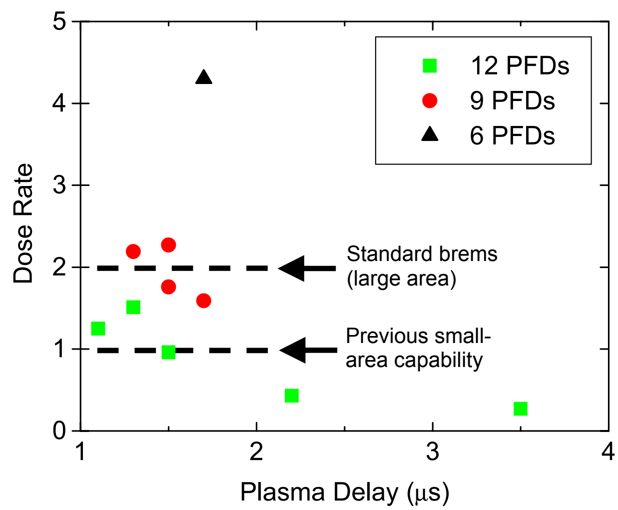

Figure 5. Dose rates for ten Saturn shots compared with levels for the standard configuration.

A fast-framing x-ray pinhole camera produces time-gated and time-integrated images of the source distribution. These data are shown for the 6-PFD shot in Fig. 6. The time-integrated image indicates six intense radiation sources, corresponding to the six individual PFDs. (The PFD return current structure was the ring-diode type for this shot, contributing to azimuthal smearing of the individual pinches.) Some variation in the time-integrated x-ray intensity from the six sources is evident (but this variation is much smaller than indicated by the near-field TLD map). The time-gated images, denoted by t1-t6, show more dramatic timing and intensity variations between the six PFDs. Intense radiation is recorded from the individual PFDs on two or at most three of the images, corresponding to individual pulse widths less than 10 ns, consistent with the Gamble II single-PFD experience. This radiation pattern resembles that from a continuous ring diode at distances greater than the PFD-PFD spacing, and should have sufficient near-field uniformity for testing purposes.

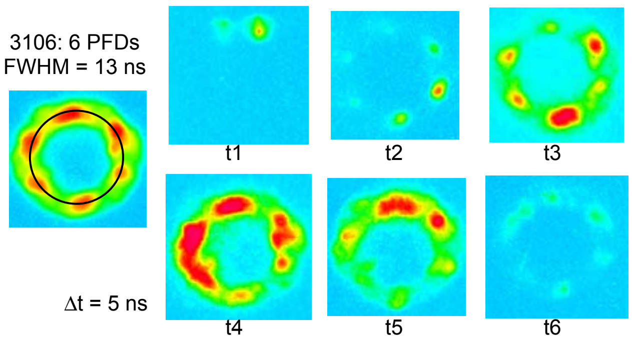

Figure 6. Time-integrated and time-gated x-ray photographs (t1-t6) from the 6-PFD shot.

In addition to the small-area dose rate and reduced pulse width, the PFD has several practical advantages for Saturn. The Z-pinch hardware uses five MITLs instead of seven for the standard configuration, so less refurbishing is required between shots and changing from Z-pinch to (small area) bremsstrahlung modes is simpler. Saturn may operate better with the PFD load, possibly because the initial short circuit phase allows current to build up in the MITLs at low voltage. The evidence for this is improved azimuthal power flow symmetry and reduced damage from "zingers" in the MITLs. The PFD hardware itself is relatively simple and inexpensive, compared with the hardware for the standard or alternative small-area configurations. The electrode gap tolerances are much less critical for the PFD, easing the setup procedure. Much of the hardware close to the load is damaged or destroyed on a shot, and can be made to be disposable. The modular nature of the PFDs make it easy to change the number and arrangement to meet specific needs.

III. ISSUES AND PLANS FOR SATURN AND DECADE

The main technical issue for this PFD system is the apparent current loss implied by the x-ray conversion efficiency. The conclusion that only 40-75% of the total generator current produces bremsstrahlung is based on radiation measurements and ITS analyses, and should be investigated further with more direct electron and ion current measurements. It may be possible to increase the fraction of current producing x-rays and thereby increase the dose rate.

Other practical issues are reproducibility and uniformity. Controlling these qualities relies on understanding the plasma parameters and their reproducibility. The plasma density distribution in this PFD configuration (Fig. 1) will be diagnosed using laser interferometry in the future.

These issues will be addressed in single-PFD experiments on Gamble II. Any modifications that lead to improvement will be implemented on Saturn.

Another application for this technique is to the DTRA Decade generator at Arnold Engineering Development Center in Tullahoma, TN. Decade is configured much like Saturn for driving Z-pinch loads, but with a 300-ns current rise time. A similar convolute system is used to converge power to a common load. It is desired to have a bremsstrahlung mode on Decade to supplement the z-pinch mode, preferably one that requires minimal time and expense to change between modes. A version of the Saturn PFD configuration will be investigated for application on Decade, first using Gamble II modified to provide a 200-ns current rise time and then scaling up to Decade itself (or possibly to Saturn in its long-pulse mode).

IV. ACKNOWLEDGEMENTS

The authors are pleased to acknowledge their collaborators at NRL and Sandia who contributed to the success of this work. V. Harper-Slaboszewicz of Sandia was the technical and programmatic leader of the Saturn experiments and provided funding for the NRL support efforts. The Sandia Saturn team provided expert support and showed a remarkable ability to operate the generator in this new mode: D. Abbate, H. Brown, J. Gergel, R. Gutierrez, B. Henderson, W. Howard, B. and K. Jones, T. Meluso, R. Michaud, K. Mikkelson, E. Miller, J. Montoya, J. Nguyen, T. Nguyen, B. Peyton, J. Rivera, R. Ross, G. Tilley, M. Torres. From NRL, R. Allen provided 3D PIC calculations to determine the isolation requirements for the PFD arrays on Saturn, S. Swanekamp provided analyses of x-ray diagnostics, D. Phipps and A. Miller participated in the Saturn experiments and E. Featherstone provided technical support for Gamble II experiments. B. Roberts labored at the scanner to provide digitized x-ray image data.

V. REFERENCES

[1] D. D. Bloomquist, et al., "Saturn, a large area x-ray simulation accelerator," in Proc. 6th IEEE Pulsed Power Conf. (Arlington, VA), p. 310 (1987).

[2] R. B. Spielman, et al., "A double post-hole vacuum convolute diode for z-pinch experiments on Saturn," in Proc. 7th IEEE Pulsed Power Conf. (Monterey, CA), p. 445 (1989).